TITLE: Sustaining an Aging Aircraft Fleet with Practical Life Enhancement Methods

Sustaining an Aging Aircraft Fleet with Practical Life Enhancement Methods

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Abstract

Extension of aircraft beyond their original design service life or operation in expanded or different roles pose challenges in continuing to operate these aircraft economically or safely. Management of the fleet generally entails increased structural inspection and maintenance, repair of inevitable fatigue damage or possible structural replacement. In a large number of cases structural elements become life limiting or require major rework due to fatigue cracks and damage originating at holes. Hole cold expansion to induce residual compressive stresses around the hole, and thereby minimize the stress concentration effect of the hole, is a proven method for retarding cracks at holes. Reworking existing structure using this technology can significantly extend the fatigue and damage tolerance life and ultimately reduce or eliminate the need for costly ongoing structural inspection while ensuring continued airworthiness without compromising performance or weapons systems capability. This paper discusses the hole cold expansion method as well as derivative technology used to repair fatigue cracked or corroded holes using high interference fit cold expanded bushings. Examples of where the technology is used to extend service lives and restore structural integrity on aging military and commercial aircraft will be presented.

Introduction

Management of an aging aircraft fleet encompasses, among other things, increased structural maintenance and repair of inevitable fatigue damage and normal wear of structural attachments. Refurbishment of the structure will typically entail repair to restore static strength with acceptable durability and damage tolerance requirements for primary structure. The challenge facing the industry and operators is how to economically achieve these objectives without compromising long-term structural integrity, imposing restrictive ongoing inspections and incorporating expensive major structural replacement and/or repair.

In a large number of cases structural elements become life limiting or require major rework due to fatigue cracks and damage originating at holes. Economical life extension has been attained without replacement of major structural elements or reduced risk to continued safe operation by use of technology that can pre-stress fatigue critical holes and damaged holes in structure and attachment lugs and fittings. Hole cold expansion is a proven method for retarding growth of cracks originating at holes. The induced residual compressive stresses minimize the stress concentration effect of the hole. In addition, these beneficial residual stresses are useful in meeting ongoing damage tolerance requirements by reducing the stress-intensity factor for residual cracks thereby permitting use of smaller initial flaw sizes in crack growth analysis. The resultant increase in fatigue and damage tolerance life can ultimately reduce or eliminate the need for costly ongoing structural inspection while ensuring continued airworthiness without compromising performance or weapons systems capability.

Repair of fatigue cracked, damaged or corroded holes can be accomplished using derivative technologies such as high interference fit cold expanded bushings and a new cold expanded rivetless nutplate system. These methods resize the damaged hole back to nominal and synergistically cold expands the surrounding material, resulting in a repair with generally a better fatigue and damage tolerance life than the "as-built" structure. Several military and commercial applications have successfully used these methods as terminating repair solutions as well as avoiding structural or component replacement. This is very beneficial when trying to manage or extend the life of aircraft as an interim measure while awaiting replacement aircraft. These proven life enhancement technologies are routinely

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incorporated into both new an aging aircraft structures and systems. Examples of applications and supporting test data are presented.

The Problem with Holes

Holes in metal structures are unavoidable in most conventional aircraft designs and are inevitably the weakest part of the structure. They concentrate stresses, intensifying the magnitude of the applied load by factors of three or more. The additions of cyclic tensile loading frequently produce crack initiation, growth and eventually fatigue failure. Small defects in the hole from manufacturing defects, tooling marks, fastener installation and repairs are stress risers that can accelerate crack initiation. Over time and enough accumulated cycles, these flaws can lead to single or multiple fatigue cracks that can result in catastrophic structural failure. The advent of damage tolerance requirements attempts to account for these "rouge" flaws in analysis to ensure structural integrity through conservatism in determining ongoing structural inspections or structural lifing.

The fatigue life of holes can be enhanced in several ways. Good hole quality, minimizing flaws; use of interference fit fasteners in the hole to modify the fatigue stress amplitude; and increasing material thickness to reduce the net section stress although it carries a weight penalty. The other way is to introduce beneficial residual stresses around the hole, which like interference fit fasteners, primarily shield the hole from the applied stress to reduce crack growth rate. This method can compliment the other methods, and carries no weight penalty. Of the methods available to induce compressive residual stresses around holes the split sleeve cold expansion method developed by Fatigue Technology Inc (FTI) is the most commonly used by the aerospace and other industries. The technology was intended for new production aircraft structures, however it has been proven effective in aging aircraft by reducing the impact of increased localized stress levels following rework and increasing the fatigue and crack growth resistance of repairs.

Overview of Split Sleeve Cold Expansion Process

Split Sleeve Cold Expansion, or the Cx process, is accomplished by using an oversize tapered mandrel pre-fitted with an internally lubricated stainless steel sleeve. A nosecap assembly restrains the sleeve in the hole while the mandrel is pulled through the hole, as shown in Figure 1. The sleeve protects the hole from damage and allows the tapered mandrel to radially expand and yield the area surrounding the hole in a repeatable, controlled manner. The sleeve also allows the process to be a one-sided operation. After cold expansion of the hole is completed, the sleeve is discarded. Mandrel insertion and sleeve removal requires no access to the backside of a component, which is an important consideration for repairing existing structure and process automation. The process can also be applied through a stack-up of multiple materials or structural elements.

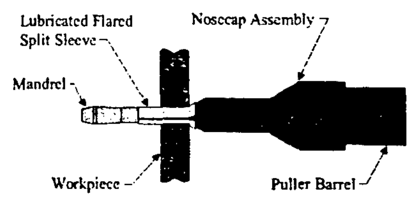

Figure 1
Split Sleeve Cold Expansion Process

Hole cold expansion improves the fatigue life of holes in metallic structure by generating a large, controllable zone of permanent residual compressive stress around the hole. A typical photoelastic pattern for a cold expanded hole (Figure 2) shows the residual stress field created by this process. These stresses are formed as a result of plastic yielding of the material caused by the mechanical expansion of the hole, and the subsequent elastic "springback" of the material lying beyond the plastically deformed hole.

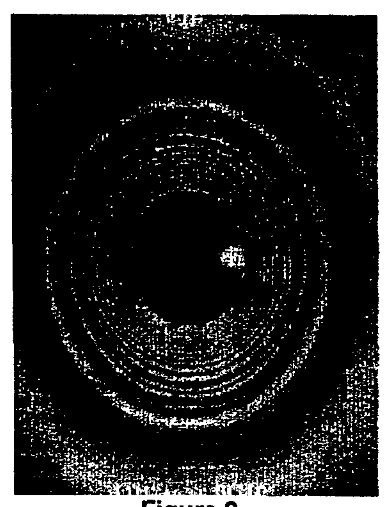

Figure 2
Residual Strain Pattern Around Cold Expanded Hole As Viewed

Typical residual radial and circumferential stresses generated by cold expansion are illustrated in Figure 3. The annular zone of compressive stress extends radially up to one diameter from the edge of the hole for typical fastener diameters and has a peak magnitude roughly equal to the compressive yield strength of the material. A balancing tensile stress zone with a peak stress of 10 to 15 percent of the material tensile yield strength lies just beyond the compressive stress region. Since it is unlikely for the applied cyclic tensile stresses to overcome the residual compressive stress, the hole is effectively shielded from the tensile stresses that propagate flaws into fatigue cracks. Fatigue life improvement from the Cx process usually ranges from 3-to-1 to 10-to-1 in typical aircraft structures.

Optimal fatigue performance is achieved when the hole is expanded by at least 3 percent for aluminum, and at least 4.5 percent for titanium and high strength steels, in typical hole diameters (up to 25 mm) and plate thickness. Cold expanded hole fatigue lives generally range from 3 to 10 times the fatigue life of similarly non-cold expanded holes as shown in Figure 4 for aluminum alloy [1] and Figure 5 for titanium [1].

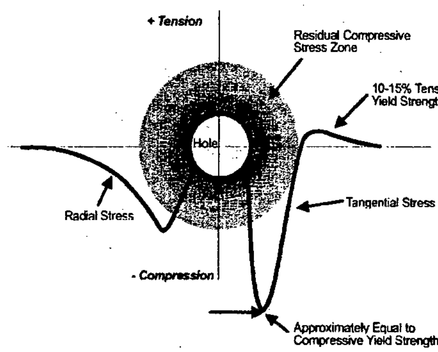

Figure 3
Typical Residual Radial and Circumferential Stress Distributions Around a Cold Expanded Hole

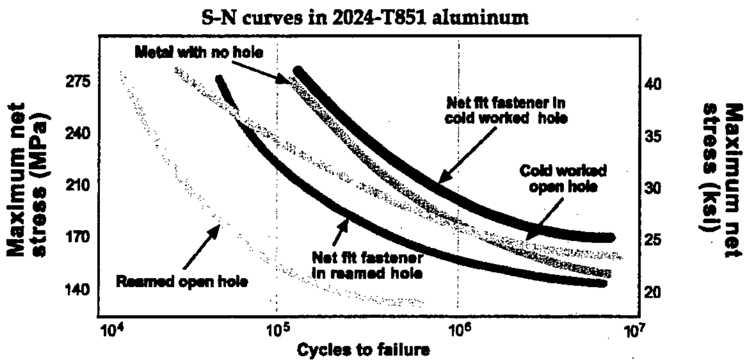

Figure 4
Fatigue Life Improvement - 2024-T851 Aluminum Alloy

Damage Tolerance

Crack growth characteristics serve as the basis for fleet structural maintenance planning for many commercial and military organizations. Durability and damage tolerance analysis (DADTA) revolutionized the USAF structural design and repair philosophy in the 1970s. Theoretical analysis of crack growth life from an assumed 0.050-inch (1.25-mm) initial flaw size and material fracture toughness characteristics, has proven a reliable and somewhat conservative technique to determine structural life and inspection cycles.

The primary effect of the cold expansion residual stresses is to reduce the crack growth rates by reducing the stress intensity factor range (ΔK) and the stress ratio (R, min. stress/max. stress). This effect is shown in Figure 6 [2]. The stress intensity factor is a measure of the stresses acting on the crack. Additionally, the presence of residual stresses may change the critical crack length for unstable fracture, because it reduces the static stress intensity factor. The reduction in crack growth rate and the increased critical crack length significantly improves the damage tolerance of the structure.

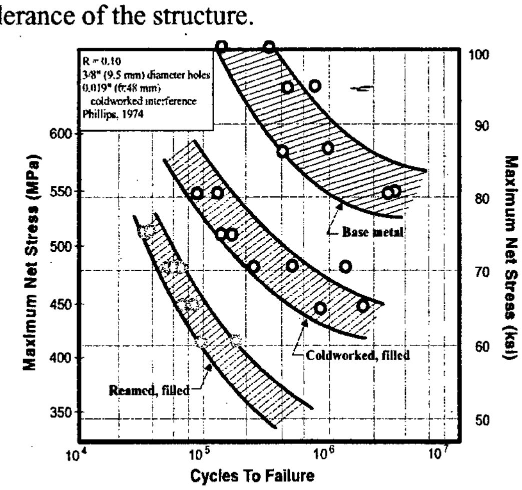

Figure 5
Fatigue Life Improvement –Titanium (6Al-4V)

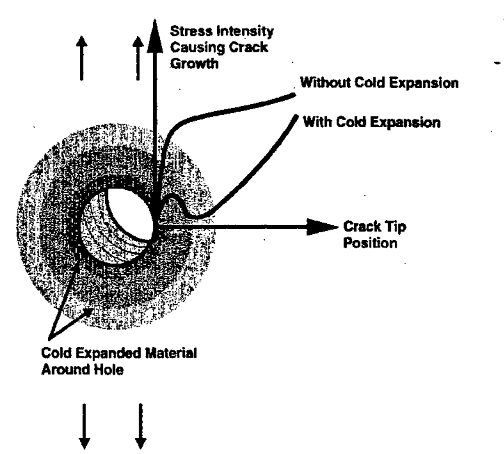

Figure 6
Reduction in Stress Intensity Factor Range Under Residual Compressive Stress

When reworking aged structure the probability of missing a crack in a hole during inspection and rework is high. The Cx process can be effective in preventing these cracks from growing. Figure 7 shows that cracks about 1mm in length growing from a 6mm (1/4") diameter hole in 7075-T6 aluminum alloy, under 248 MPa (35 ksi) net stress, are totally arrested when subjected to the same applied cyclic loads [3]. The residual compressive stress zone acts like a strong clamp on the material around the crack minimizing crack opening displacement, thereby preventing growth. The process is just as effective in high-strength steel and titanium [4]. Fatigue life improvement of 3:1 is typical.

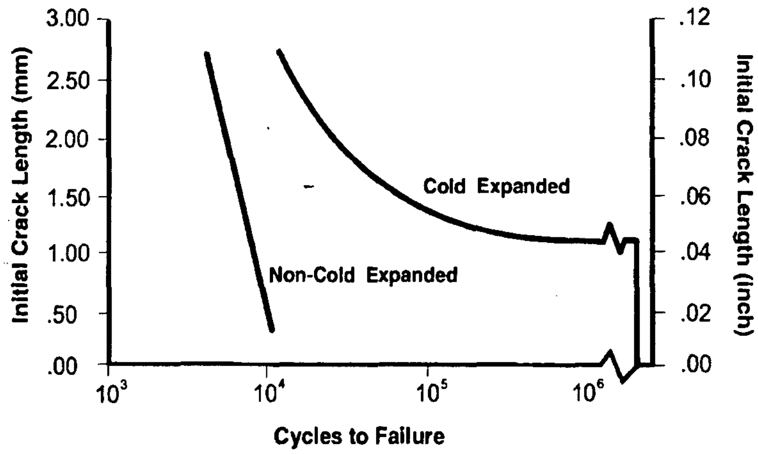

Figure 7
Effect of Cold Expansion on Stopping Crack Growth (7075-T6 Aluminum)

Results from crack growth tests incorporating cold expansion of holes prompted a revision of the DADTA initial flaw size philosophy. For many aircraft in the USAF, advantage is taken of the crack retardation benefits of cold expansion by reducing the initial flaw size to as small as 0.005 inch (0.125 mm) if cold expansion is incorporated. The same philosophy could be applied to repairs on other aging military aircraft and commercial aircraft for fatigue-related service bulletin repairs.

Rework of Previously Cold Expanded Holes

Although hole cold expansion has traditionally been used in new production and repair of fatigue damaged structure, the general perception is that once utilized, the beneficial residual compressive stresses induced could not be improved upon, thereby limiting future rework options. Extensive tests and investigations [5] revealed that additional split sleeve cold expansion of these holes can further enhance the damage tolerance and fatigue life, particularly after a period of cyclic strain aging from in-service structural loads.

The resultant increase in fatigue life after rework is comparable to, or exceeds, the life of initially cold expanded holes. The Cx process performs well even when cracks (up to 1.25 mm for the conditions tested) are present. The evaluations and subsequent in-service evaluations showed conclusively that holes may be cold expanded multiple times with commensurate fatigue life improvement making it a very versatile process for rework of aging structures.

Life Cycle Cost Benefits

Split sleeve cold expansion is a measurable and quantifiable way of improving the fatigue life and quality of the hole without relying on the integrity of the fastener fit. The overall result is enhanced fatigue life, which can allow flying an aircraft that might otherwise have reached its fatigue limit.

Life cycle cost benefits derived from use of this process include: (1) Added safety and operational assurance through improved structural integrity, both in production and repair; (2) Reduced maintenance costs by virtual elimination of fatigue problems associated with fastened joints; and (3) Reduced inspection costs, by extending inspection intervals resulting from the enhanced fatigue/durability and damage tolerance of the structure.

The additional cost of incorporating cold expansion of holes, in either production or repair applications, is practically insignificant in comparison with the total cost of preparing the joint and installing the fastener. The overall airworthiness, structural integrity and operational safety benefits far outweigh any additional process costs.

Applications of Hole Cold Expansion on Aging Aircraft

The split sleeve cold expansion process has been used to repair and restore structural integrity and fatigue life to a large number of aged aircraft that were operating at or beyond their original design life. In many cases it has been used to enable aircraft to reach the original design life after premature or unpredicted structural fatigue problems were encountered due to design deficiencies, increased operational load spectrum, or changing roles of the aircraft.

Aircraft such as the F-4, T-38, F-16 (which includes cold expansion of a number of non-round hole configurations), F-111, B-52, KC-135, B-2, F-14, F-15, F-18, C-141, C-5, C-130, Mirage III, Tornado, EA-6B, JSTARS (Boeing 707)—virtually all Western World military and commercial aircraft—incorporate the cold expansion process to some extent or another. It has been effective in repair of existing structure without major structural replacement that otherwise would have been cost prohibitive or uneconomical to repair. The principles of hole cold expansion have been applied to derive other processes used to repair badly damaged holes, including expansion of repair bushings and will be discussed next.

Repairing Damaged Holes

Damaged or discrepant holes are common in aircraft production and structural repair or modification programs. Damage induced by drilling or mis-alignment requires oversize of fasteners or in extreme cases bushing or plugging of the hole to reposition it or remove all incipient damage. In repair of aging aircraft, removal of fatigue or corrosion damage in holes necessitates similar oversizing and frequently needs application of splice repairs or component replacement.

The use of cold expanded bushings in repairs result in a convenient high integrity repair with generally a better fatigue and damage tolerance life than the original structure. Several military and commercial aircraft applications have successfully used these methods as terminating repair solutions.

Derivative Cold Expansion Processes

The principles of hole cold expansion are used to provide the interference fit required for bushing installation in structural components. Bushing interference is defined as the degree to which the bushing outside diameter is greater than the inside diameter of the hole. Traditional techniques using cryogenic fluids or dry ice to shrink the bushings are limited to diametrical interference of 0.05 to 0.075 mm (0.002 to .003 inch). Fatigue Technology Inc. has derived a process and tooling under the trade name of ForceMate® (FmCx™), which has the ability to achieve interference of 0.1 to 0.225 mm (.004 to .009 inch) in a nominal 25-mm (1.0-inch) diameter bushing. A schematic of the ForceMate process is shown in Figure 8. Besides being a convenient way to install high interference fit bushings, cold expanded bushings are an effective way to repair damaged holes in structures.

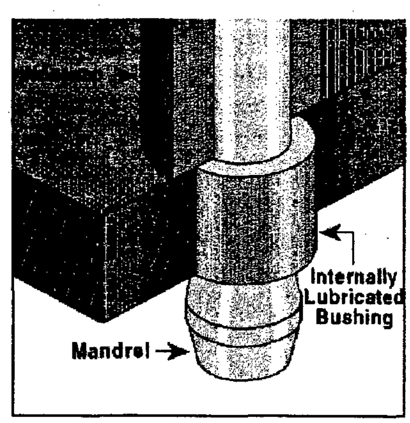

Figure 8
Typical ForceMate Process

There are three methods of installing cold expanded bushings that have been developed by FTI. These methods are:

1. ForceMate® which installs initially clearance fit bushings with high interference fit resulting in significant fatigue life improvement,
2. BushLoc® A convenient repair/resizing bushing with high interference fit using a variation of the split sleeve cold expansion process, and
3. ForceTec® A rivetless nut plate, which can be used for repairing fatigue damage associated with conventional riveted nut plate installations.

Each of these methods has its own merits and benefits.

Besides the higher retention forces and ease of installation, cold expanded bushings are superior to shrink and press fit bushings in many ways. The primary advantage is the fatigue and crack growth life improvement resulting from the unique state of residual stress around the hole. Increasing the fatigue life reduces the need for frequent inspections and increases the overall integrity of the repair. The typical life improvement, ranging from 3:1 to greater than 20:1, allows the cold expanded bushing to be used as an integral part of a terminating repair.

The action of cold expanding the bushing generally imparts compressive residual stresses around the hole, depending on the bushing/parent material combination, that reduce the mean stress at the hole thereby improving fatigue life. The high interference fit of the bushing acts to reduce the stress amplitude at the hole and works synergistically to significantly improve fatigue and crack growth lives of both new and repair bushing installations as shown in Figure 9.

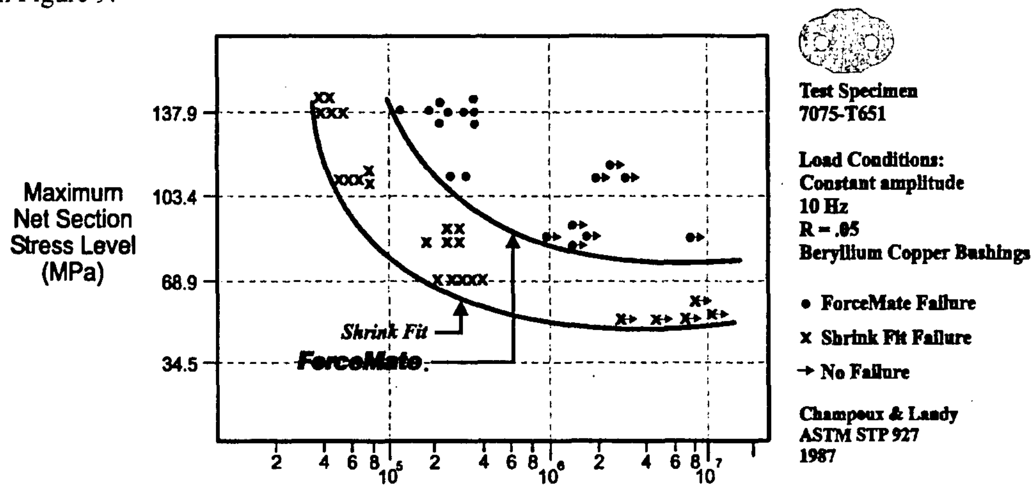

Figure 9
Fatigue Life Comparison of Shrink Fit and ForceMate Bushing Installations

Each of the cold expansion bushing process comes in a wide variety of diameters and lengths to meet just about any application. ForceMate bushings can be made to meet the most exacting specifications including dimension, tolerance, and material. The BushLoc process offers the greatest flexibility for cold expanded repair bushing installation. Just about any combination of bushing length, inside diameter and outside diameter can be installed with this process. The manufacturing/rework tolerances of holes and repair bushing are generally wider than standard bushings.

Figure 10 shows a multi-layered stack-up with individual segmented bushings. All three bushings are installed simultaneously. Different outside diameter bushings can be simultaneously installed allowing minimum material removal to correct hole discrepancies or ~~to~~ remove corrosion damage or fatigue cracks.

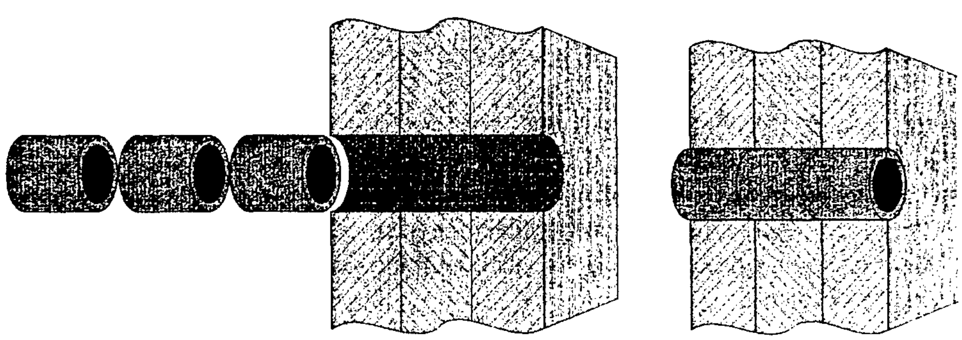

Figure 10
Schematic of Multiple Bushing Installation

BushLoc™ Bushing Installation Process

This process was primarily designed to repair or re-size damaged fastener holes and has been successfully used in these applications. The installation of a bushing using BushLoc is accomplished using specially designed tooling similar to that used to spilt sleeve cold expanded a hole.

The method is currently used on a large number of repairs to existing aircraft and has eliminated the need to replace major structural components such as the inner to outer wing (rainbow) fitting on the C-130 transport aircraft. Thousands of holes are repaired on the aging Boeing 707 aircraft being refitted for the JSTARS program. The superior benefits of cold expanded bushings in fatigue, damage tolerance, improved corrosion resistance, ease of installation and the flexibility of adapting to almost any repair configuration, gives a technically and economically advanced alternative to traditional repair methods. The cost of using cold expanded bushings is generally similar to the cost of conventional repairs with the added benefit of providing terminating repair action or at least reduced inspections, and reduced follow-on maintenance costs.

BushLoc Applications

In a spanwise splice repair evaluation for military transport aircraft, FTI completed a test program comparing the spectrum fatigue life of both FTI's BushLoc hole repair and resizing process and the ForceTec Rivetless nut plate system in a short edge distance application. The test was conducted on 7075-T6511 pre-cracked, short edge margin aluminum specimens taken from actual wing structure. The original 1/4 inch diameter [edge margin (e/D) =2.0] holes were pre-notched and the crack grown to a part-through surface length up to 0.070 inch. A portion if not all of the pre-crack was removed when preparing the bushing repair starting hole. Residual crack lengths for the repaired holes ranged from not visible (zero) to 0.025 inch. The holes were installed with BushLoc bushings and ForceTec retainers to determine the crack growth life of the repaired holes. All specimens, baseline and repaired, were tested at the same gross stress. This means that repaired specimens were tested at higher net stresses due to metal removal. The repairs reduced the edge margin from 2.0 to a range of 1.25 to 1.4 depending on the repair bushing diameter. Results of these tests are shown in Figure 11.

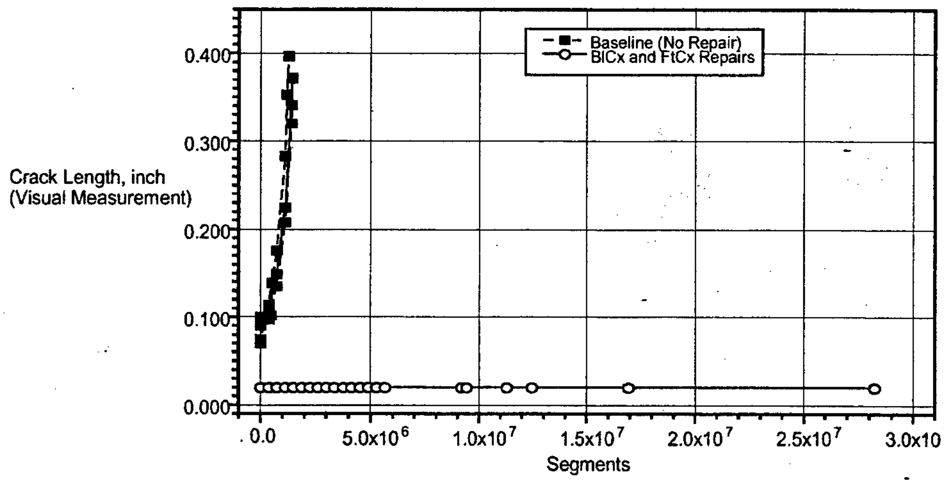

Figure 11
Crack Length Versus Segments

All repaired specimens ran to run-out life of 45,405 flight hours with very little or no additional crack growth when repaired with either BushLoc or ForceTec.

In another commercial aircraft BushLoc repair, extensive testing was performed to simulate the repair of a spar cap to wing skin fastener hole on a commercial aircraft. The repair was to remove a large crack from the spar cap without removing the skin or oversizing the original 3/8-inch fastener hole in the wing skin. Several bushing repairs were examined. In one case, a 1/8-inch wall thickness BushLoc bushing was installed. The load transfer test coupon configuration is shown in Figure 12.

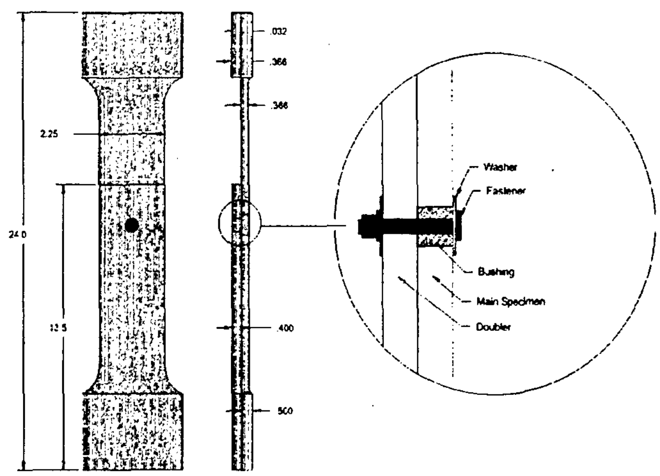

Figure 12
Load Transfer Test Specimen

A typical commercial aircraft wing spectrum load was applied to the specimen and results for various repair scenarios were compared to baseline (fastener only) configured specimens. Test results in Figure 13 show that specimens repaired using either aluminum or steel BushLoc bushings performed better than the baseline configuration and were substantially better than shrink-fit repaired specimens. Results of this BushLoc test were accepted by the FAA as terminating repair actions for this location, which further justified its use in a number of other military and commercial rework applications.

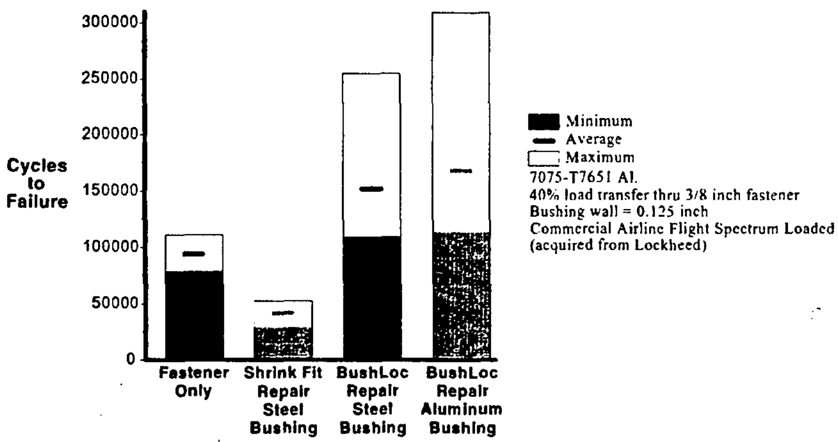

Figure 13
Comparison of Fatigue Life for BushLoc Repaired Specimens

ForceTec Rivetless Nut Plate Process

The last method to be reviewed is the ForceTec rivetless nut plate process shown schematically in Figure 14. While this system is not specifically a bushing installation method it does have a bushing like member (called a retainer) that is installed in the hole and offers the potential for terminating repairs of riveted nut plates. The installed retainer provides superior fatigue performance when compared to riveted nut plates by virtue of the beneficial residual stress imparted to the material surrounding the hole. The resultant high interference fit of the retainer provides resistance to torque and removal forces normally encountered during fastener installation and removal. ForceTec retainers meet and exceed the demanding torque and push-out requirements of MIL-N 25027 and can be used as a substitute for most riveted type nut plates.

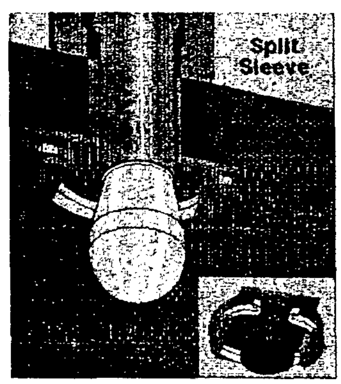

Figure 14
Schematic of ForceTec Rivetless Nut Plate Installation

By way of an example of the use of ForceTec in a rework situation, the upper fuselage skin of the F-16 has been identified as an area requiring fatigue life improvement for the aircraft to meet its service life objective. This area of the F-16 has a number of access panels secured with conventional riveted nut plates as shown in Figure 15. The highly loaded corners of the cutouts are developing fatigue cracks from either the fastener holes or the attaching rivet holes of the nut plate.

The proposed repair included removing the riveted nut plates, cold expansion of the attaching nut plate rivet holes and installation of an expanded ForceTec rivetless nut plate. Following an extensive coupon and component test program where the specimens were tested at the severe F-16 fighter spectrum load, the repaired configuration showed a four times life improvement over the initial configuration. Additional testing of simulated access panels with ForceTec installed originally, the life of the specimen exceeded 12 times the life of the original riveted configuration [6]. This economical structural life enhancement modification is now specified for this particular fleet of aircraft.

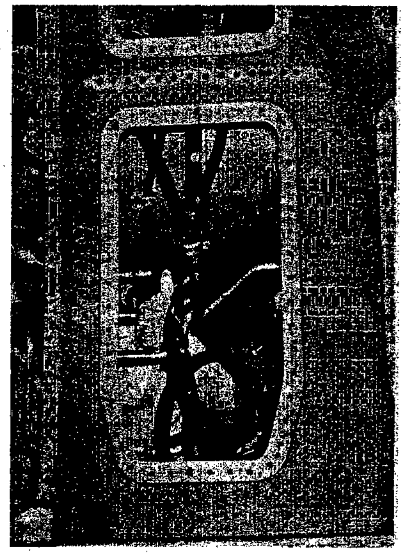

Figure 15
Panel in F-16 Fuselage Skin

Review of FTI Processes Used to Repair Aging Aircraft Structures (and New Production)

The summary list of applications shown in Attachment A is intended to give examples of hole-related structural problems, and the FTI process/product used to overcome or resolve these problems. The list is by no means complete, as the technology is used in an extensive number of actual aircraft applications to enhance the fatigue life of a structure, possibly extend inspection intervals, or provide terminating repair action. In many cases the processes are being used to repair previously "un-repairable" primary and secondary structure and components such as the C-130 Rainbow Fitting and engine mounting struts. New uses for the technology are continually evolving as needs arise. Where indicated in the list, there is ongoing research and development to adapt or apply the product/process to a particular application.

Summary

With the shrinking defense budgets and cost of procuring new weapons systems continuing to escalate, it is necessary to prolong or extend the life of existing aircraft fleets. Structural fatigue along with corrosion are two of the primary life-limiting causes of structural replacement or retirement. Fatigue cracks originating at holes can be effectively eliminated by pre-stressing the material surrounding the hole in compression using the split sleeve cold expansion method. Over many years of successful application extending the fatigue and crack growth lives of numerous aging military and commercial aircraft, the process can be confidently used to overcome hole-related fatigue problems. Furthermore, the use of expanded bushings and rivetless nut plates, derived from the cold expansion methodology can be used to repair damaged or defective holes in existing structures to generate terminating repairs and thereby, avoid costly structural replacements. The cold expansion processes can effectively and economically be used to sustain an aging aircraft fleet by extending the fatigue life and damage tolerance of the structure without compromising structural integrity, airworthiness or the operational role of the weapons system platform.

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[6] Ransom, J., et al; "F-16 Fighting Falcon Upper Fuselage Skin Fatigue Life Enhancement," USAF Aircraft Structural Integrity Program Conference, 1999.

Questions

The following questions with answers were presented at the conclusion of the paper.

Q1 How does quality control affect the protection afforded by cold working? (C. Smith)

A1 The cold working process, while critical in its application, is relatively insensitive to minor manufacturing discrepancies such as hole finish. The process tolerances are also within normal manufacturing tolerances for most handheld tooling operations. Within the system of cold working tooling for a particular hole size, Fatigue Technology Inc. would supply "checking fixtures" that quickly verify correct starting hole tolerance, verify correct hole retainer expansion (enlargement) for the application, and also a checking GO/NO-GO gauge to periodically check that the mandrel major diameter is within tolerance for the process. If these process quality checking/verification fixtures are used, then correct hole processing is assured.

Q2 What percent of manufacturers are using this process during production? (J. Komorowski)

A2 Virtually all manufacturers of commercial transport and military aircraft in the western world use the process selectively for meeting design fatigue life goals, structural weight reduction or damage tolerance objectives. A large number of commuter aircraft and helicopter manufacturers also use the process. The ForceMate bushing installation method is extensively used in helicopter rotor assemblies and also across the board for engine and stores pylons, landing gear and wing attach fittings, and also for repairing damaged holes in these and other structural locations.

Q3 How extensive is the use of the ForceTec rivetless nut plate system and for what applications? (F. Grimsley)

A3 The ForceTec system is being used both in production and repair/replacement of existing fatigue-prone/damaged riveted nut plate installations as briefly mention in the paper. This nut plate is the first to be approved for primary structural attachments and major sub-assembly connections. The repair on the F-16 is being effectively carried out at depot level and a number of other field repair installations have also been done, on both commercial and military aircraft.

It is also worthy of note that on the F-16 application the installations are being done without the need to provide secondary sealing after installation. The sealing qualities of ForceTec were thoroughly tested to cover installation in fuel tank locations on the F-22. This feature saves rework time and cost, and omits a particularly messy post-sealing operation.

Attachment A
Summary of FTI Processes Used to Repair Aging Aircraft Structures (and New Production)

Structural Problem or Application	FTI Process	Mature	Requires R&D
Hole-related fatigue —Open or filled hole —Non-circular holes —Short edge margin (e/D) condition —Multiple-material stack-up (includes different materials) —Attachment lugs —Close proximity holes —Damage tolerance improvement —Increasing inspection interval	Split Sleeve Cold Expansion™ (SsCx™)	Yes	No
Temporary stop drill repairs	StopCrack™	Yes	No
Mis-drilled holes Installation of interference fit bushings	BushLoc® BushLoc	Yes Yes	No No
Bushing of holes —Repair of holes —Fatigue life enhancement of lugs —Improve damage tolerance of lugs —Installation of high interference fit bushings —Rework/resizing of holes in lugs —Elimination of bushing migration —Improved corrosion resistance of bushed holes —Elimination of vibration-induced bushing problems —Replacement of bushings in wing attach lugs	ForceMate®	Yes	No
Blind nut plate installations —Increased fatigue life of nut plates —Blind attachment of primary structures —Repair of fatigue-prone attaching structure with riveted nut plate attachment —Installation of blind threaded insert	ForceTec® DuraLoc	Yes Yes	Ongoing R&D Ongoing R&D
Mounting of components/systems —Attaching hydraulic hoses/electrical wiring —Mounting electrical connectors (i.e., cannon plug) through structures	 ForceTec/DuraLoc with stud/standoff Adaptation of ForceMate	 Yes Yes	 Ongoing R&D No
Repair of components/structure —Repairing corroded/cracked/oversize mounting holes (pylons/struts, etc.) —Repairing cracked access panel mounting —Repairing wing fold transmission attaching hole (corrosion/fatigue) —Installing blind threaded insert —Repairing helicopter blade attachment —Fatigue of hydraulic ports in actuators —Repairing aircraft wheels —Repairing wheel fuse plug holes	 ForceMate ForceTec ForceMate DuraLoc ForceMate SsCx/ForceMate Split Sleeve Cold Expansion Split Sleeve Cold Expansion	 Yes Yes Yes Yes Yes Yes Yes	 Ongoing R&D for new applications No Ongoing R&D No No

Structural Problem and Application	FTI Process	Mature	Requires R&D
Composite panel repairs		Yes	Ongoing R&D
—Resizing damaged holes	GromEx® and ForceMate		
—Increased durability of load transfer joint	GromEx and ForceMate		
—Increased resistance to lightning strike	GromEx and ForceMate		
—Blind nut plate installation	ForceTec/DuraLoc		
—Hole reinforcement	ForceTec/GromEx		
—Realignment of mis-drilled holes	ForceMate		
Engine Components			
—Fatigue life improvement of holes	Split Sleeve Cold Expansion	Yes	No
—Repair/resizing blade attach holes	ForceMate	Yes	Ongoing R&D